The lithium-rotation correlation for WTTS in Taurus-Auriga

L.F. Xing [a b,**], J.R. Shi and J.Y. Wei [a,**]

[a] *National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China*

[b] *Graduate University of the Chinese Academy of Sciences, Beijing 100049, China*

Abstract

Surface lithium abundance and rotation velocity can serve as powerful and mutually complementary diagnostics of interior structure of stars. So far, the processes responsible for the lithium depletion during pre-main sequence evolution are still poorly understood. We investigate whether a correlation exists between equivalent widths of Li (EW(Li)) and rotation period (P_{rot}) for Weak-line T Tauri stars (WTTSs). We find that rapidly rotating stars have lower EW(Li) and the fast burning of Li begins at the phase when star's P_{rot} evolves towards 3 days among 0.9$M_{\odot}$ to 1.4$M_{\odot}$ WTTSs in Taurus-Auriga. Our results support the conclusion by Piau & Turch-Chiéze about a model for lithium depletion with age of the star and by Bouvier et al. in relation to rotation evolution. The turn over of the curve for the correlation between EW(Li) and P_{rot} is at the phase of Zero-Age Main Sequence (ZAMS). The EW(Li) decreases with decreasing P_{rot} before the star reaches the ZAMS, while it decreases with increasing P_{rot} (decreasing rotation velocity) for young low-mass main sequence stars. This result could be explained as an age effect of Li depletion and the rapid rotation does not inhibit Li destruction among low mass PMS stars.

Key words: stars: Li abundance — stars: evolution — stars: pre-main-sequence

* Corresponding author.

** Corresponding author.

Email addresses: `lfxing602@yahoo.com.cn`, `sjr@bao.ac.cn`, `wjy@bao.ac.cn` (J.R. Shi and J.Y. Wei).

[1] Supported by the National Science Foundation of China

1 Introduction

T Tauri stars (TTS) are very young ($\leq 10^8$yr), low-mass (M$\leq 2M_\odot$), late spectral type (late G to M) pre-main sequence (PMS) stars, still in the process of gravitational contraction. They are of particular interest to stellar evolution, among other things because they are, if sufficiently young, in a fully convective stage of evolution. T Tauri stars are usually divided into two classes, namely Classical T Tauri stars (CTTSs) and Weak lined T Tauri stars (WTTSs). The former ones are associated with a circumstellar disk, from which they accrete material at a rate of about 10^{-7}M$_\odot$ yr $^{-1}$, while the later ones lack such disks.

At the beginning of the T Tauri phase of the base of the convective zone is too cool to allow lithium burning. As the star evolves on the pre-main sequence the deep regions of convective zone temporally exceed the ^{7}Li burning point in typical stellar condition (2.5×10^6K), and surface Li can be transported to this region and depleted during PMS evolutionary phase. The ^{7}Li abundancds of stars therefore offer a directly insight over stellar internal structure and evolution as it is extremely sensitive to the appearance of the radiative core. The surface Li abundances and surface rotation velocity can serve as powerful and mutually complementary diagnostics of interior structure(Strom, 1994).

Based on the result of Bouvier et al. (1993) from a study of the connection between EW(Li) and P$_{rot}$ of 10 CTTSs and 6 WTTSs, we concentrate on the connection between EW(Li) and P$_{rot}$ for more WTTSs. We did not consider CTTS, since accretion leads to a replenishment of lithium at their surface for CTTSs (Bouvier et al., 1993), such that the Li-abundance cannot be used as a diagnostic for the interior. Also, the mass and the age for WTTSs derived from theoretical tracks and isochrones are more reliable than those for CTTSs. We performed a new and homogeneous analysis of all the Li data and P$_{rot}$ available in the early literature for WTTSs in the range of mass 0.9-1.4M$_\odot$.

It is known that Li depletion increases with decreasing stellar mass, and with increasing metallicity (Proffitt & Michaud, 1989). Soderblom et al. (1993, their Fig. 9) investigated the relationship between Li abundances and masses for ZAMS stars in the Pleiades clusters, and found that, when the mass of the stars ranges between 0.9M$_\odot$ to 1.4M$_\odot$, the Li abundances do not strongly depend on the mass. We selected a sample of WTTS stars in the range of mass 0.9-1.4M$_\odot$ in Taurus-Auriga star forming regions (SFRs, in a same nebular, star has the similar metallicity).

We concentrate on the connection between the EW(Li) and P$_{rot}$. First, since the Li I λ6707 line is very strong in T Tauri stars, it is on the saturated part of the curve of growth, so small errors in the measured Li I strength will lead to large error in the derived abundances (Duncan, 1991). Using just the EW(Li) can avoid some uncertainties propagated from uncertainties of T_{eff} estimates which are provided by the estimates from (B-V) and (V-I) colors. Second, the measurements of rotation velocity $v \sin i$ yields only a lower limit to the rotation velocity due to the unknown angle of inclination, i. We use both the directly observed EW(Li) and P_{rot} instead of Li abundance and rotation velocity of stars in our rotation-lithium study.

This paper is organized as follows. The periods and Li data of WTTSs are presented in Sect. 2. The relationship between EW(Li) and $P_{\rm rot}$ and discussion provided in Sect. 3. And the results are summarized in Sect. 4.

A The Rotation periods and Li data

We selected from the literature a sample of WTTSs which according to their position in the H-R diagram are in the mass range from $0.9M_\odot$ to $1.4M_\odot$, and whose EW(Li) and $P_{\rm rot}$ have been determined. The location of the stars in the H-R diagram is shown together with theoretical pre-main sequence evolutionary tracks in Fig. 1. The theoretical pre-main sequence evolutionary tracks were taken from Cohen & Kuhi (1979). The known binaries have been rejected, since the late-type binary system may be tidally locked rotation, which lead naturally to slower lithium destruction rates (Maccarone et al., 2005).

A.1 Rotation periods

Our sample consists of 21 WTTSs in the range of mass 0.9-1.4$M_\odot$ in Taurus-Auriga. In table 1, the up-to-date rotation periods and equivalent widths are presented for our sample stars. The rotation periods of these stars are taken directly from the following literature:

- The periods of WTTSs from Bouvier et al. (1993) are shown table 1. Our sample includes the objects with a multi-site photometric campaign to monitor T Tauri stars over more than two month by Bouvier et al. (1993). Two methods, namely the string-length method and periodogram analysis, were used to derive the $P_{\rm rot}$ for ten WTTS stars, most of them with confidence level larger than 99%. The secondary sample of Bouvier et al. (1993, their Table 4) is also included. Totally, we selected seven WTTSs from their sample.
- Xing et al. (2006) selected a sample of X-ray sources that have been identified as WTTS stars around the Taurus-Auriga SFRs. They monitored the light variations for 22 WTTSs and obtained the $P_{\rm rot}$ for 12 stars using two

methods: the Phase Dispersion Minimization (PDM) and Fourier analysis methods (PERIOD04), most of them with confidence level large than 99%. We took seven WTTSs from their sample.

- Bouvier et al. (1997) monitored the light variations of 58 WTTSs and derived photometric periods for 18 stars using 3 methods: the periodogram analysis, CLEAN deconvolution algorithm and string-length estimator. Except for RXJ0409.2+2901, all periods are detected at the 99% confidence level in the periodogram. Five objects have been taken from their sample.
- Grankin (1993) presented the results of BVR photometry of 22 WTTSs. They obtained rotation periods for ten stars. Two WTTSs were selected from this sample.

A.2 Equivalent widths of Li

The equivalent widths of Li for the above stars are taken directly from the following literature:

- The EW(Li) of the Bouvier et al. (1993) sample were taken directly from Basriet et al. (1991). They reported the observations of strong Li I λ6707 line in 28 T Tauri stars in the Taurus-Auriga star formation complex. Line strengths were obtained using high resolution spectra from the Hamilten echelle at Lick Observatory. They have corrected the Li I equivalent widths for continuum veiling based on a simultaneous measurement of the actual veiling present.
- The EW(Li) of the Bouvier et al. (1997) sample and three stars (RX J0430.8+2113, RX J0405.1+2632 and RX J0432.7+1853) of the Xing et al. (2006) sample were taken directly from Wichmann et al. (2000). They presented a detailed study for Li-rich stars discovered by ROSAT in Taurus-Auriga SFRs, the results are based on high-resolution echelle spectra.
- The Li I equivalent widths of the Grankin (1993) sample and the star NTTS045251+3016 from Xing et al. (2006) were taken from the list of Walter et al. (1988), measured from high-dispersion spectra.
- Two stars of the Xing et al. (2006) sample, [LH98]37 and [LH98]53, were identified as WTTSs by Li & Hu (1998), and the Li I equivalent widths were taken from their results, which are based on the intermediate resolution spectra. The EW(Li) of HD 287927 was taken from Walter (1986), also based on the intermediate resolution spectrum.

B Results and discussion

B.1 Li-rotation for WTTS

We plotted the EW(Li) versus P_{rot} for our sample stars in Fig. 2. This shows that there is a clear correlation between the EW(Li) and P_{rot}, i.e. the rapid rotators have lower EW(Li) and the depletion of lithium proceeds fast, when the rotation period of star evolves towards 3 days for WTTSs with mass between $0.9M_{\odot}$ and $1.4M_{\odot}$ in Taurus-Auriga SFRs.

Our results are in good agreement with the hypothesis that surface Li depletion takes place during PMS evolution for low-mass stars as a result of Li burning via (p, α) reactions at low temperatures of $T \geq 2.6 \times 10^6$K (King et al., 2000). These results support the conclusion by Piau & Turck-Chiéze (2002, their Fig. 4) about a model for lithium depletion with age of star. Their results predict that the surface Li depletion will take place during PMS evolution for low-mass stars. They also distinguish two phases in lithium depletion: (1) a rapid nuclear destruction in the T Tauri phase before 20 Myr whatever the mass in the range between 0.8 and $1.4M_{\odot}$, and (2) a second phase where the destruction is slow and moderate, which is largely dependent on the hydrodynamic instability located at the base of the convective zone.

It is important to know whether the EW(Li) depends on the masses or not. We plotted the EW(Li) against the masses for our sample stars in Fig. 3. This indicates that the EW(Li) of our sample stars does not show any trend as a function of mass. It means that the EW(Li) do not depend on the mass of WTTSs for our sample stars.

In order to further confirm our result, we plotted the EW(Li) against P_{rot} for WTTSs in Orion in Fig. 4. The EW(Li) and P_{rot} of these stars are taken directly from Alcala et al. (1996) and Marilli et al. (2005). These selected stars are late G or early K-type stars whose masses are close to the masses of WTTS sample in Taurus-Auriga (since the mass is not direct observable, except in eclipsing binaries, it would be better to use T_{eff} or spectral type to estimate the mass (Martín, 1997). In the absence of a luminosity determination for these stars, the range of mass was estimated from the spectral type of the stars). Fig. 4 shows that the correlation between EW(Li) and P_{rot} of WTTSs (late G and early K-type) in Orion nebula is in a good agreement with that one of WTTSs ($0.9M_{\odot} \leq M \leq 1.4M_{\odot}$) in Taurus-Auriga. It is evident that the rapidly rotating stars have lower EW(Li), although the stars in Taurus-Auriga differ from that in Orion in some aspects.

B.2 Li-rotation for young solar type stars

The lithium-rotation relation for ZAMS stars in Pleiades (e.g. Tschäpe & Rüdiger, 2001) and young low-mass man sequence stars (e.g. Rebolo & Beckman, 1988; Chaboyer, 1998) has long been known. In "older" clusters (Pleiades, Hyades) the faster rotating stars show less the Li depletion (Tschäpe & Rüdiger, 2001). In order to compare the possible effect of rotation upon lithium depletion between young solar-type main sequence stars and PMS, we take the P_{rot} and EW(Li) for 7 ZAMS stars (Krishnamurthi et al., 19980; Soderblom et al., 1993; Messina, 2001) in the Pleiades cluster and 12 young low-mass main sequence stars (Rebolo & Beckman, 1988) in the Hyades cluster, and plotted the EW(Li) versus P_{rot} of these stars with WTTSs in our sample in Fig. 5. The spectral types of these young stars were in the range between late G and early K-type (in the range of mass 0.9-1.4$M_{\odot}$, determined from mass-temperature relation given by Soderblom et al. (1993)). The EW(Li), $P_{\rm rot}$ and other stellar properties of these stars in Pleiades and Hyades clusters are shown in table 3.

Fig. 5 shows that the turn over of the lithium-rotation relation curve is at ZAMS phase. The EW(Li) decreases with decreasing P_{rot} when stars young than ZAMS, whereas EW(Li) decrease with increasing P_{rot} (decreasing rotational velocity) when stars are on the ZAMS or older.

These results are in good agreement with the rotation evolution model (e.g. Bouvier et al., 1994; Soderblom et al., 1993; Cemeron et al., 1995; Keppens et al., 1995) and Li could serve as a "clock" of stellar evolution in the PMS phase (Drake, 2003). The rotation evolution model and the results of these observations indicate that the main features of the rotation evolution of low-mass, late type stars are the strong PMS spin up from moderate rotation in the T Tauri phase to ultrafast rotation at ZAMS and an increase of the rotation period of star (spin down) with increasing age for main sequence stars.

The relation between EW(Li) and P_{rot} in Fig. 5 also shows that rapid rotators have lower EW(Li). This result is consistent with the lithium-age correlation in the sense that there is less lithium in the surfaces of older WTTSs (Post-TTSs) than in young WTTSs. e.g. the EW(Li) of older WTTSs (TAP 9 whose location in H-R diagram very near ZAMS star) is lower than that of young WTTSs (TAP 57 whose location in H-R diagram still on Hayashi line).

C Summary

In this work we have discussed the correlation of lithium-rotation. Our main conclusions can be summarized as:

- At least for WTTSs with mass between $0.9M_{\odot}$ and $1.4M_{\odot}$ in Taurus-Auriga Nebula, there is a clear correlation between EW(Li) and P_{rot}, i.e. on average, rapidly rotating stars have lower equivalent widths of Li. That can be explained as an age effect of Li depletion during pre-main sequence. It is clear that rapid rotation does not inhibit Li depletion among low mass PMS stars.
- The fast burnings of Li begin at the phase when the rotation period of the star evolves to approach 3 days. And the surface lithium depletion always happens during the PMS phase.
- The turn over of the lithium-rotation connection curve at the phase of ZAMS. The equivalent widths of Li decreases with decreasing rotation period when stars are younger than ZAMS, whereas the equivalent widths of Li decreases with increasing rotation period (decreasing rotation velocity) when stars evolve beyond the ZAMS.

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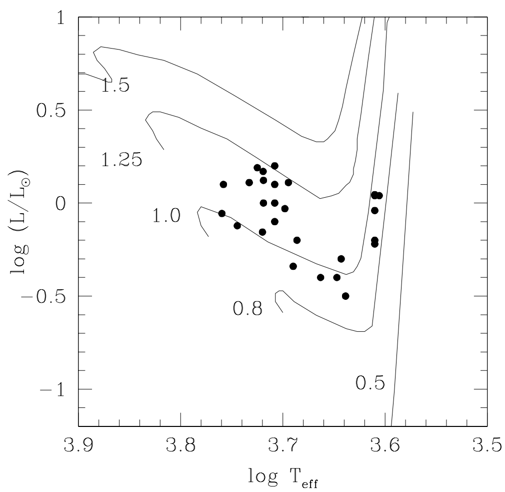

Fig. .1. HR diagram for our sample stars (filled circle). The pre-main-sequence tracks were taken from Cohen & Kuhi (1979). These stars fall in the mass range between $0.9M_{\odot}$ to $1.4M_{\odot}$.

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Table .1
Rotational periods and stellar properties for 21 WTTSs. Reference to table 1: X&L: Xing et al. (2006) and Li & Hu (1998); X&W: Xing et al. (2006) and Wichmann et al. (2000); X&Wa: Xing et al. (2006) and Walter (1986); X&G: Xing et al. (2006) and Gregorio-Hetermet & Hetem (2002); B: Bouvier et al. (1993); G&W: Grankin (1996) and Walter et al. (1988); B&W: Bouvier et al. (1997) and Wichmann et al. (2000). The mass of stars are taken directly from above literature or from comparison with evolutionary tracks of Cohen & Kuhi (1979).

Star	P_{rot}(d)	$\log(L_*/L_\odot)$	SpT.	T_{eff}	EW(Li)(mÅ)	$M(M_\odot)$	ref
The sample of Xing et al. photometry							
$[LH98]37$	1.13	0.12	K0IV	5236	240	1.2	X&L
$[LH98]53$	0.728	-0.05	G2IV	5792	230	1.0	X&L
HD 287927	0.772	-0.12	G5	5554	200	0.98	X&G
NTTS 045251+3016	9.12	0.04	K5	4034	580	0.9	X&Wa
RX J0405.1+2632	1.93	-0.34	K2	4897	219	0.94	X&W
RX J0430.8+2113	0.741	0.19	G8	5309	141	1.27	X&W
RX J0432.7+1853	1.55	-0.1	K1	5105	253	1.1	X&W
The sample of Bouvier et al. (1993) photometry							
V1068 Tau	3.37	0.04	K7	4060	510	0.9	B
V836 Tau	7.0	-0.22	K7	4060	570	0.9	B
NTTS 045226+3013	2.24	0.17	K0	5240	440	1.2	B
NTTS 034903+2431	1.6	-0.3	K5	4395	370	1.03	B
NTTS 041636+2743	5.64	-0.04	K7	4060	600	0.9	B
RX J043005.1+181351	2.7	0.11	K2	4950	420	1.24	B
RX J043214.9+182013	3.75	0.045	K7	4060	570	0.9	B
The sample of Bouvier et al. (1997) photometry							
RX J0409.2+2901	2.74	0.0	K1	5105	413	1.2	B&W
RX J0415.4+2044	1.83	0.0	K0	5236	270	1.1	B&W
RX J0423.7+1537	1.605	-0.2	K2	4855	361	1.0	B&W
RX J0438.7+1546	3.07	0.1	K1	5105	419	1.2	B&W
RX J0457.2+1524	2.39	0.2	K1	5105	446	1.4	B&W
The sample of Grankin (1993) photometry							
NTTS 041559+1716	2.52	-0.4	K7	4438	530	0.93	G&W
NTTS 042835+1700	1.55	-0.52	K5	4352	150	0.88	G&W

Table .2
Rotation periods and stellar properties for 9 stars in Pleiades clusters and 14 stars in Hyades clusters. Reference to table 2: M&S: Messina (2001) and Soderblom et al. (1993); R: Rebolo & Beckman (1988)

Pleiades clusters stars

HII number	P_{rot} (d)	SpT.	T_{eff} °K	EW(Li) m$\mathring{A}$	ref
263	4.82	G8V	5060	290	M&S
345	0.84	G8V	5160	245	M&S
738	0.83	G9V	5140	203	M&S
1039	0.784	K2V	4720	333	M&S
2244	0.56	K2.5V	4720	268	M&S
882	0.581	K3V	4500	212	M&S
1883	0.235	K2V	4560	282	M&S
3197	0.44	K3v	4440	302	M&S
1653	0.74	K4.5Ve	4220	108	M&S

Hyades clusters stars

BD+	Period (d)	SpT.	T_{eff} °K	EW(Li) m$\mathring{A}$	ref
19 694	9.2	G5	5460	32	R
17 707	9.1	G8V	5570	29	R
18 623	5.5	G0V	6060	86	R
16 589	6.2	G0V	5930	72	R
16 592	7.9	G2V	5840	69	R
18 636	6.1	G5V	5650	70	R
15 624	5.1	G0	6070	84	R
16 601	8.5	G2V	5770	51	R
15 627	5.9	G0	6200	85	R
16 606	7.4	GV	5920	82	R
17 731	3.2	G0	6340	19	R
17 734	11.4	G5	5230	3	R
15 642	9.0	G5	5540	15	R
15 651	6.5	G0	5940	84	R

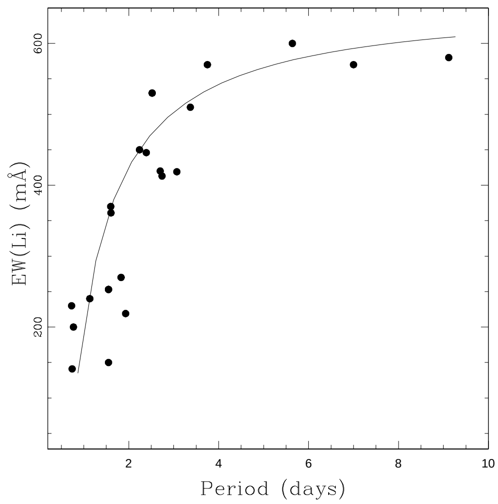

Fig. .2. Lithium $\lambda 6707$ equivalent widths of WTTSs (mass range $0.9\mathrm{M}_{\odot} \leq M \leq 1.4 M_{\odot}$ in Taurus-Auriga SFRs) as a function of the rotation periods.

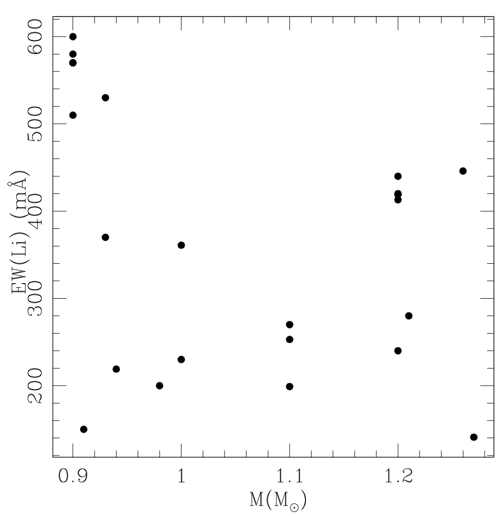

Fig. .3. Lithium $\lambda 6707$ equivalent widths of WTTS (mass range cover by $0.9\mathrm{M}_{\odot} \leq M \leq 1.4 M_{\odot}$ in Taurus-Auriga SFRs) as a function of their masses.

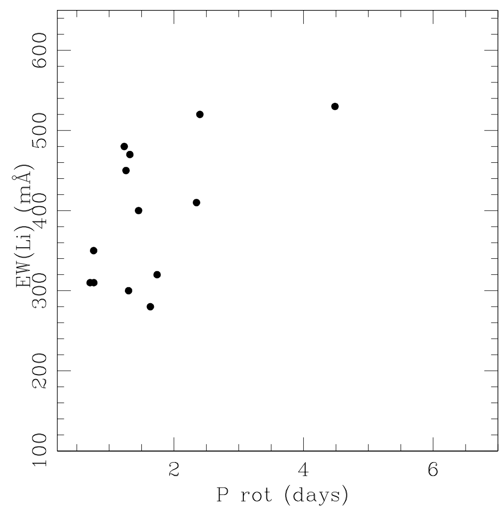

Fig. .4. Lithium $\lambda 6707$ equivalent widths for WTTSs in Orion nebula as a function of their rotational periods. The spectral type of sample stars ranges from G9 to K5.

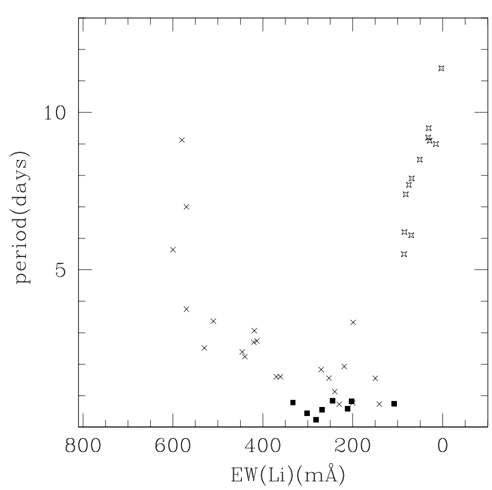

Fig. .5. The lithium $\lambda 6707$ equivalent widths as a function of the rotational periods of WTTSs of mass $0.9\mathrm{M}_{\odot} \leq M \leq 1.4 M_{\odot}$ in Taurus-Auriga SFRs (crosses), ZAMS stars between late G and early K-type in Pleiades cluster (filled square) and young solar-like stars between late G and early K-type in Hyades cluster (stars).